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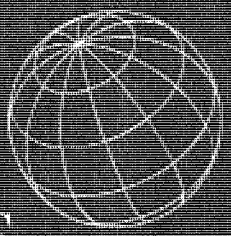

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On the Wells report

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In the current "Deflategate" controversy, the New England Patriots have been accused of illicitly deflating footballs before the start of their 2015 American Football Conference championship game against the Indianapolis Colts. The National Football League and the lawyers it hired have produced a report—commonly known as the "Wells report"—that has been used to justify penalties against the Patriots and quarterback Tom Brady. Although the Wells report finds that the Patriots footballs declined in pressure significantly more than the Colts balls in the first half of the game, our replication of the report's analysis finds that it relies on an unorthodox statistical procedure at odds with the methodology the report describes. It also fails to investigate all relevant scenarios. In addition, it focuses only on the difference between the Colts and Patriots pressure drops. Such a difference, however, can be caused either by the pressure in the Patriots balls dropping below their expected value or by the pressure in the Colts balls rising above their expected value. The second of these two scenarios seems more likely based on the absolute pressure measurements. Logistically, the greater change in pressure in the Patriots footballs can be explained by the fact that sufficient time may have passed between halftime testing of the two teams' balls for the Colts balls to warm significantly, effectively inflating them.

In 2012, two of us (Hassett and Veuger) performed a statistical analysis of injury data and investigated whether that data supported the contention that New Orleans Saints players were statistically more likely to injure opponents than players on other teams. We found that, in fact, the Saints players injured fewer competing players than all but one team during the first year of their supposed "bounty" program, and that there was no evidence over the entire period that the Saints injured more players than the typical team. Following our testimony before former National Football League (NFL) Commissioner Paul Tagliabue, the NFL's penalties against the Saints players were withdrawn, and news accounts have pointed to our analysis as contributing to that decision.

In the current "Deflategate" controversy in which the New England Patriots have been accused of illicitly deflating footballs before the start of the 2015 American Football Conference championship game, the NFL and lawyers it hired have produced a report that has been used to justify penalties against the Patriots and, specifically, Tom Brady (Wells Jr., Karp, and Reisner 2015).[1] The Patriots received a $1 million fine and lost two draft picks, which the team declined to appeal (Jones 2015). The NFL Players Association (NFLPA) has appealed Tom Brady's suspension and criticized the report as biased (Jones 2015). For example, NFLPA Executive

[1] Hereinafter, we refer to the report as the "Wells report," its colloquial referent.

Director DeMaurice Smith said the report "delivered exactly what the client wanted" (CBS Boston 2015). On the other hand, the experts employed by the NFL have solid credentials and deserved reputations.

Given that our impartiality was in the past at least implicitly recognized by the NFL and Commissioner Tagliabue, we believe we are a uniquely qualified third party to evaluate the merits of the evidence provided in the Wells report. In this paper, we review the Wells report, attempt to replicate its statistical analysis, and explore its possible shortcomings.

Our findings are as follows. First, the Wells report contains sufficient data to explore the question of whether the Patriots deflated their footballs using statistical techniques. Second, the Wells report's statistical analysis cannot be replicated by performing the analysis as described in the report. Third, the Wells report's results can (for the most part) be replicated when we use a different, flawed modeling approach that fundamentally differs from the approach described in the report. Fourth, the Wells report failed to recognize the importance of the logical link between two of its areas of inquiry: whether the Patriots balls were deflated more than the Colts balls, and whether the Patriots balls were at a pressure that could be explained without recourse to wrongdoing by the Patriots.

When correct tests are performed, the evidence points to a conclusion that is inconsistent with the Wells findings. Our evidence suggests a specific sequence of events. The Wells report conclusions are likely incorrect, and a simple misunderstanding appears to have led the NFL to these incorrect conclusions.

Did the Patriots Balls Experience a Larger Pressure Drop Than the Colts Balls?

In this section, we begin by replicating the Wells analysis. Then, we discuss the dependence of the analysis on assumptions concerning which pressure gauges were used. Finally, we provide a thorough analysis of all the possible permutations of measurement-device combinations.

Replicating the Core Wells Analysis

The core contribution of the Wells report is a statistical analysis that appears to demonstrate that the Patriots balls exhibited a greater pressure decline between the pregame and halftime pressure measurements than the Colts balls. In this section, we review the authors' methodology and attempt to replicate their findings. We find, as the Wells report did, that the evidence suggests on balance that the Patriots balls declined in pressure more than the Colts balls under the maintained assumptions in the report. As we will explain, however, this does not necessarily constitute evidence that the Patriots illegally tampered with their footballs.

From the report, a clear picture of the ball measurement process emerges. Referee Walt Anderson measured the pressure of the balls before the game at 12.5 pounds per square inch (PSI) for the Patriots and 13.0 or 13.1 PSI for the Colts (Wells Jr., Karp, and Reisner 2015, 52). During halftime, Clete Blakeman and Dyrol Prioleau, alternative referees, measured the pressure of 11 balls from the Patriots and 4 balls from the Colts. At least one of the gauges used was the same gauge Anderson used before the game. Blakeman and Prioleau could measure only four of the Colts balls because they were nearing the end of halftime and needed the balls for the game (Wells Jr., Karp, and Reisner 2015, 7; 69).

Perhaps the most important contribution the report purports to make lies in its analysis of these data. After all, if the rigor of statistical analysis supports the claim that the Patriots illegally deflated their footballs, this would constitute strong evidence of wrongdoing on their part. The Wells report describes its approach as follows: The statistical model that serves as the baseline for estimating the effects of the various variables "expresses the pressure drop associated with a single halftime measurement as composed of a series of additive terms" (Wells Jr., Karp, and Reisner 2015, A-3). More specifically, the report claims to present estimates derived from the following equation, which expresses the decrease in ball pressure for a given ball (ijk) as a function of a constant term (μ), team-fixed effects (α_i), gauge/official-fixed effects (β_j), their interaction,

and two error terms:

$$D_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \tau_{ijk} + \epsilon_l$$

This equation suggests that a multiple regression analysis was performed. But when we estimate the regression described in the report, the results are quite different from those reported by the authors. After some trial and error, though, we were able to replicate almost all of the results presented. Table 1 shows the values presented in Table A-2 in appendix A of appendix 1 on page A-4 of the Wells report, alongside the results of our best attempts to replicate them. As one can see, the estimated effects match perfectly for all of the listed effects, with the exception of "Gauge."

The precision with which all but two of our table 1 estimates match those of the Wells report renders it extraordinarily unlikely that our attempts to replicate the data presented in table A-2 of the Wells report used anything but the same analysis used to generate those values in the report. Yet the regression specification used to produce these results—and, presumably, those of the Wells report—is certainly not a standard specification.

Although the text that prefaces table A-2 indicates that the values are "adjusted for other effects," implying the authors performed a multiple regression, they seem to be the result of simply including no other explanatory variables (and excluding a constant term). For instance, the regression that estimates the "Team effects" includes no other variable besides "Team." The interaction-term effects are estimated from an equation that includes only the four interaction terms and specifies the lack of a constant term. That is, the equations that were actually estimated appear to be of the following form, where d_y represents a dummy variable for category $y = 1 \ldots Y$ and where Σ sums over 1 through Y:

$$\text{PSI}_{Drop(\text{team } i, \text{ gauge/official } j, \text{ ball } k)} = \Sigma[\beta_y d_{y,ijk}] + \epsilon_{ijk}$$

For instance, in the case of the category of "Team," there would be two dummy variables, $d_{PATRIOTS}$ and d_{COLTS}. This approach of estimating a variable's effect while omitting other variables produces biased estimates and is at odds with the description in the report of the approach taken, which describes an approach that would have been closer to the norm.

This replication is consistent with the balance of the Wells results, but not with the report's description of its methods. In the next section, we show results for an appropriate analysis of the data that roughly confirms the Wells results on the relative pressure decline but contradicts it in a crucial way.

Table 1. Replicating the Wells Report

Effect	Team	Gauge	Wells values	Replicated values
Team	Colts	#N/A	-0.469	-0.4687
Team	Patriots	#N/A	-1.202	-1.2022
Gauge	#N/A	A	-0.883	-1.12
Gauge	#N/A	B	-0.788	-0.8933
Team*Gauge	Colts	A	-0.375	-0.375
Team*Gauge	Colts	B	-0.563	-0.5625
Team*Gauge	Patriots	A	-1.391	-1.3909
Team*Gauge	Patriots	B	-1.014	-1.0136

Notes: This table reports, in the right-most column, the authors' best attempt to replicate the coefficients featured in Table A-2 of the Wells report. To the left of that column are the coefficients featured in the Wells report. The authors generated the replicated values using the equation referenced in the three paragraphs preceding this table rather than the equation the Wells report leaves the impression of having used. The equation the Wells report leaves the impression of having used features a single multivariate regression, yet the equation that replicates most of their results runs each set of variables in a separate regression.
Source: Authors' calculations based on Theodore Wells Jr., Brad S. Karp, and Lorin L. Reisner, *Investigative Report Concerning Footballs Used during the AFC Championship Game on January 18, 2015* (Paul, Weiss, Rifkind, Wharton & Garrison LLP, May 6, 2015), http://online.wsj.com/public/resources/documents/Deflategate.pdf.

Two Different Gauges

The Patriots and Colts balls were, according to Anderson's best recollection, measured by him at 12.5 and 13.1 PSI, respectively, before the game. This measurement was the starting point for the investigation. Anderson had two different pressure gauges, one that the report refers to as the "Logo" gauge, as it has a logo on it, and one referred to as the "Non-Logo" gauge.

At halftime, 11 of the Patriots balls and only 4 of Colts balls were measured with both gauges. Unfortunately, the Logo gauge tends to give higher readings than the Non-Logo gauge (by about 0.4 PSI), and this has created some controversy. Anderson remembers that he used the Logo gauge before the game, but the Wells report, in a direct contradiction of that recollection, concludes that he used the Non-Logo gauge before the game. The Patriots have argued that this decision was crucial to the analysis and that the evidence of excessive deflation disappears if one assumes the Logo gauge was used. Wells, in a news conference after the report was released, has stated that his report's results continue to hold and that "it doesn't matter because regardless of which gauges were used the scientific consultants addressed all of the permutations in their analysis" (*Boston Globe* 2015).[2]

This statement is factually incorrect. The Wells report neither provides evidence for every possible permutation of gauge use nor proves that the report's conclusions are independent of gauge use. If, as the Wells report asserts, Anderson's recollection is unreliable, then it seems to logically follow that one way to perform a thorough analysis would be to address all four possible permutations of gauge use.

Two gauges and two teams implies four possible permutations of pregame gauge use: (1) the Patriots balls were measured with the Logo gauge whereas the Colts balls were measured with the Non-Logo gauge, (2) the Patriots balls were measured with the Non-Logo gauge whereas the Colts balls were measured with the Logo gauge, (3) both teams' balls were measured with the Logo gauge, or (4) both teams' balls were measured with the Non-Logo gauge. We analyze each possibility separately using a standard statistical model.

Tables 2–5 show the results of statistical analysis for all four possible permutations. They are estimates from an equation of the following form, where μ is a constant, N_k is a count variable for the order in which ball k was measured, $I_{Patriots}$ is an indicator variable for whether the ball belonged to the Patriots, and ϵ is an error term:

$$PSI_{Drop(k)} = \mu + \alpha N_k + \beta I_{Patriots} + \epsilon_k$$

The variable of primary interest is the coefficient on the dummy variable for the Patriots, β. If β is positive and statistically significant, it would indicate that the drop in pressure of the Patriots balls between their pregame and halftime pressure measurements was statistically distinguishable from the drop in pressure of the Colts balls between their measurements. If Wells is correct in asserting that the choice of gauge has no effect on the outcome of analysis, then β should be positive and statistically significant at the 5 percent level in each of the four possible gauge permutations.[3] But as we will see, it is not.

Tables 2–5 show the analysis for each of the four possible pregame gauge scenarios, with three different cuts of the data: one with the observations stacked so that each of the two measurements of each ball at halftime is treated as an independent observation, one with the observations generated by the Logo gauge at halftime, and one with the observations generated by the Non-Logo gauge at halftime.[4]

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[2] Page 114 of the Wells report makes a claim that is for all intents and purposes synonymous: "According to both Exponent and Dr. Marlow, the difference in the average pressure drops between the Patriots and Colts footballs is statistically significant. The conclusion was consistent regardless of the assumptions made as to which of the two gauges was used to measure the game balls prior to the game and at halftime."

[3] We adopt the 5 percent confidence interval from the Wells report as our significance threshold. As noted on page 11 in the Exponent section of the Wells report, "The convention in statistical applications is to declare a finding significant if the p-value is less than 0.05."

[4] We include specifications that sort each set of halftime observations by gauge because it seems plausible to assume that the distribution of errors would be different for each halftime gauge, and running them in a single regression fails to account for this possibility.

Table 2. Pregame Gauge Assumption: Logo Gauge for Both Teams

		Constant	Order	Patriots
Stacked	Coefficient	0.033	0.025	.820**
	t-stat (p-value)	.09 (.927)	1.02 (.315)	3.46 (.002)
Logo gauge	Coefficient	0.205	0.020	0.689
	t-stat (p-value)	.40 (.693)	.57 (.577)	2.02 (.066)
Non-Logo gauge	Coefficient	-0.14	0.030	0.952*
	t-stat (p-value)	-.26 (.800)	.80 (.436)	2.63 (.022)

Notes: This table shows the coefficients and statistical significance metrics for each of the three variables included in our preferred regression specification: a "Constant" term (the inclusion of which is standard practice), an "Order" variable that numbers the balls 1–15 based on the order in which they were tested, and a "Patriots" dummy variable that has a value of 0 in the case of the Colts and a value of 1 in the case of the Patriots. The "Stacked" set of coefficient and corresponding significance rows show the regression results if you include the observations generated by both the Logo and Non-Logo gauges during the halftime measurement process as separate observations, the two Logo gauge rows below that show the regression output if you include only the 15 observations generated by the Logo gauge during halftime, and the two Non-Logo gauge rows include the regression output if you only include the 15 observations generated by the Non-Logo gauge during halftime. The data used in this specification of the regression assume that the Logo gauge was the gauge that Anderson used to measure the balls of both the Patriots and the Colts before the game. * indicates significance at a 5 percent confidence level; ** indicates significance at a 1 percent confidence level.
Source: Authors' calculations based on Theodore Wells Jr., Brad S. Karp, and Lorin L. Reisner, *Investigative Report Concerning Footballs Used during the AFC Championship Game on January 18, 2015* (Paul, Weiss, Rifkind, Wharton & Garrison LLP, May 6, 2015), http://online.wsj.com/public/resources/documents/Deflategate.pdf, A-4.

Table 2 shows that, under the assumption that the Logo gauge was used to measure both teams' balls before the game, whether the Patriots variable is significant depends on which cut of the data is used. The stacked regression and the Non-Logo gauge regression are significant, whereas the Logo gauge regression is not.

Table 3 shows that the Patriots variable is not significant at the 5 percent level in any of the three specifications if you assume that before the game the Logo gauge was used to measure the Patriots balls while the Non-Logo gauge was used to measure the Colts balls.

Table 4 shows that under the assumption that the Non-Logo gauge was used to measure the Patriots balls while the Logo gauge was used to measure the Colts balls, the Patriots variable is significant with all three cuts of the data. And table 5 shows that, under the assumption that the Non-Logo gauge was used to measure the balls of both teams before the game as with table 2, the result is sensitive to which cut of the data is used.

These results, in aggregate, contradict Wells's claim that the analysis yields the same result

Table 3. Pregame Gauge Assumption: Logo Only for Patriots

		Constant	Order	Patriots
Stacked	Coefficient	0.433	0.025	0.420
	t-stat (p-value)	1.23 (.231)	1.02 (.315)	1.77 (.088)
Logo gauge	Coefficient	0.605	0.020	0.289
	t-stat (p-value)	1.19 (.255)	.57 (.577)	.85 (.413)
Non-Logo gauge	Coefficient	0.260	0.030	0.552
	t-stat (p-value)	.48 (.637)	.80 (.436)	1.53 (.153)

Notes: This table shows the coefficients and statistical significance metrics for the same equation as table 2 does and presents the data in the same way. However, this specification of the regression assumes that Anderson used the Logo gauge for the Patriots and the Non-Logo gauge for the Colts when generating his pregame pressure readings.
Source: Authors' calculations based on Theodore Wells Jr., Brad S. Karp, and Lorin L. Reisner, *Investigative Report Concerning Footballs Used during the AFC Championship Game on January 18, 2015* (Paul, Weiss, Rifkind, Wharton & Garrison LLP, May 6, 2015), http://online.wsj.com/public/resources/documents/Deflategate.pdf, A-4.

Table 4. Pregame Gauge Assumption: Logo Only for Colts

		Constant	Order	Patriots
Stacked	Coefficient	0.033	0.025	1.220**
	t-stat (p-value)	.09 (.927)	1.02 (.315)	5.14 (.000)
Logo gauge	Coefficient	0.205	0.020	1.089**
	t-stat (p-value)	.40 (.693)	.57 (.577)	3.20 (.008)
Non-Logo gauge	Coefficient	-0.140	0.030	1.352**
	t-stat (p-value)	-.26 (.800)	.80 (.436)	3.74 (.003)

Notes: This table shows the coefficients and statistical significance metrics for the same equation as table 2 does and presents the data in the same way. However, this specification of the regression assumes that Anderson used the Logo gauge for the Colts and the Non-Logo gauge for the Patriots when generating his pregame pressure readings. * indicates significance at a 5 percent confidence level; ** indicates significance at a 1 percent confidence level.
Source: Authors' calculations based on Theodore Wells Jr., Brad S. Karp, and Lorin L. Reisner, *Investigative Report Concerning Footballs Used during the AFC Championship Game on January 18, 2015* (Paul, Weiss, Rifkind, Wharton & Garrison LLP, May 6, 2015), http://online.wsj.com/public/resources/documents/Deflategate.pdf, A-4.

Table 5. Pregame Gauge Assumption: Non-Logo for Both Teams

		Constant	Order	Patriots
Stacked	Coefficient	0.433	0.025	0.820**
	t-stat (p-value)	1.23 (.231)	1.02 (.315)	3.46 (.002)
Logo gauge	Coefficient	0.605	0.020	0.689
	t-stat (p-value)	1.19 (.255)	.57 (.577)	2.02 (0.066)
Non-Logo gauge	Coefficient	0.260	0.030	0.952*
	t-stat (p-value)	.48 (.637)	.80 (.436)	2.63 (.022)

Notes: This table shows the coefficients and statistical significance metrics for the same equation as table 2 does and presents the data in the same way. However, this specification of the regression assumes that Anderson used the Non-Logo gauge for the Patriots and the Colts when generating his pregame pressure readings. * indicates significance at a 5 percent confidence level; ** indicates significance at a 1 percent confidence level.
Source: Authors' calculations based on Theodore Wells Jr., Brad S. Karp, and Lorin L. Reisner, *Investigative Report Concerning Footballs Used during the AFC Championship Game on January 18, 2015* (Paul, Weiss, Rifkind, Wharton & Garrison LLP, May 6, 2015), http://online.wsj.com/public/resources/documents/Deflategate.pdf, A-4.

regardless of which set of assumptions about the two gauges was used.[5] Three of the four runs with the stacked data suggest that the Patriots balls deflated more than the Colts balls in the first half, making it "more likely than not" that illegal tampering occurred—if one assumes a statistically significant difference between the pressure drops experienced by each team to necessarily constitute evidence of illegal tampering. Yet even this inference is not independent of assumptions about which gauges were used when. As noted earlier, this analysis deals with the Wells report's assertion that Anderson's recollection is unreliable by regarding all of the four possible gauge-use permutations as equally likely and therefore granting each of the four possible permutations equal weight when formulating an inference based on the aggregation of the results. But other approaches are nevertheless possible.

For instance, one might make the assumption that Anderson used the same gauge to measure both the Colts and Patriots footballs before the game, but still remain uncertain as to which of the two gauges that single gauge was. In such a

[5] Running clustered versions of our regressions (in other words, specifications that allow the standard errors to be correlated for observations regarding the same team, gauge, or ball) yields very similar results to those reported in Tables 2–5.That is not extraordinarily surprising: even the teams' balls do not have statistically significantly different variances in their pressure levels.

case, the results would be statistically significant in the specification that analyzes the stacked observations from both gauges at halftime and in the specification that analyzes only the observations generated by the Non-Logo gauge at halftime, but not in the specification that analyzes only the observations generated by the Logo gauge at halftime. Again, this would seem to be evidence that lends credence to the claim that illegal tampering of the balls occurred—if one assumes a statistically significant difference between the pressure drops experienced by each team to necessarily constitute evidence of illegal tampering.

However, even an unequivocal finding of a statistically significant difference between the pressure drops of the Patriots and of the Colts does not necessarily constitute evidence of illegal deflation. We explain why in the next section.

Can Ambient Temperature Changes Explain the Pressure Difference between the Patriots and Colts Balls?

The pressure of a football depends on the ambient temperature of the atmosphere in which it is located. Footballs inflated to 12.5 PSI at room temperature will drop in pressure when taken into the cold. The pressure in the football will increase when it is brought back into a warm room. Estimating how much the pressure in the ball will decline when the external temperature changes involves straightforward physics.

An investigation that identifies wrongdoing on the part of the Patriots should document three things: that the pressure in the Patriots balls declined more than the pressure in the Colts balls, that the pressure in the Patriots balls was significantly below the level predicted by basic physics, and that the pressure in the Colts balls was not statistically above or below the level predicted by basic physics. The confluence of these three results would represent a smoking gun. However, the statistically different reduction in pressure could result either because the Patriots balls declined more than predicted or because the Colts balls declined less than predicted. The Wells report provides no statistical analysis on this key point.

The problem here is that ideally, measurements would have been taken simultaneously for all balls, outdoors, at the end of the half, and with the same gauge that was used before the game. Instead, the balls were taken inside and measured there, but not measured simultaneously. The pressure was checked twice for the Patriots balls (once with each gauge), after which the Patriots balls were reinflated and the Colts ball pressure was measured. Only 4 of the Colts balls (instead of all 12) were measured because halftime ended and the officials ran out of time. The fact that the officials ran out of time is highly material: it implies that the Colts balls were inside a warm room for almost the entire halftime before they were measured and thus had a chance to warm up.

The Wells report's analysis focuses on the pressure drop of the Patriots balls between their pregame and halftime measurements relative to the pressure drop of the Colts balls between their pregame and halftime measurements. The question the report attempts to answer is whether the pressure drop of the Patriots balls can be explained as the natural pressure drop of a football used during the game, or whether only human intervention can explain the pressure reduction.

Fortunately, the Wells report provides sufficient data to test this. First, it specifies the range of pressures that the Ideal Gas Law suggests the balls could have read given the temperature change from indoors to outdoors. That range, according to the report, is 11.32 to 11.52 in the case of the Patriots and 11.80 to 12.00 in the case of the Colts (Wells Jr., Karp, and Reisner 2015). Again, as there is uncertainty concerning which gauge was used before the game, we explore all four possible permutations.

The Wells report also documents that the temperature of the surrounding environment influences the internal pressure of a football even over very short time intervals. The report notes, for instance, that the 0.7 PSI impact on a football of "vigorous rubbing" dissipates after a window of roughly 15–30 minutes. And a chart on page 31 of the Exponent section of the Wells report shows pronounced effects of air temperature on ball

Table 6. The Patriots Balls at Halftime

		Pregame gauge	
Halftime gauge		High	Low
	High	0.166	.528**
	Low	-0.211	0.151

Notes: This table shows the average distance of the halftime measurements of the Patriots balls from the bottom of the range implied by the Ideal Gas Law for each of the four possible permutations of pregame and halftime gauges. ** indicates significance at a 1 percent confidence level.
Source: Authors' calculations based on Theodore Wells Jr., Brad S. Karp, and Lorin L. Reisner, *Investigative Report Concerning Footballs Used during the AFC Championship Game on January 18, 2015* (Paul, Weiss, Rifkind, Wharton & Garrison LLP, May 6, 2015), http://online.wsj.com/public/resources/documents/Deflategate.pdf, A-4.

pressure in a span of what appears to be roughly 15 minutes (Wells Jr., Karp, and Reisner 2015, 31).

The report also notes that halftime was scheduled to last 13 minutes and that the Colts balls were measured toward the very end of that window, when they ran out of time. We can therefore infer that the Colts balls were tested after being indoors for a period of a bit less than 15 minutes. The first of the Patriots balls was measured right at the beginning of halftime, followed by the others.

The differences in the pressure drop of each team's balls between pregame and halftime that are documented by the Wells report can be explained by this difference in the timing of measurements. Tables 6 and 7 report the results of a t-test for whether the pressure of the balls measured at halftime is statistically distinguishable from the bottom of the range predicted for the beginning of based on the Ideal Gas Law.[6] In principle, one could take into account the duration of exposure to the ambient temperature of the Officials' Locker Room, where the halftime testing occurred, when forming a benchmark for what the pressure of the each team's balls should measure if there were no illegal tampering.

Yet the officials' failure to record the precise time at which the balls were tested during halftime precludes the possibility of making precise adjustments for the expected pressure of the balls based on their exposure to the room's ambient temperature. The values shown in tables 6 and 7 are the average distance from the bottom of that range; a negative value indicates that it is below the value implied by the Ideal Gas Law. Separate tests are run for the observations generated by each of the two gauges at halftime, and results are reported for both possible pregame gauges.

As table 6 shows, the Patriots balls do not significantly deviate from the prediction of the Ideal Gas Law in the direction that one would expect based on the Wells report's conclusions and the NFL's disciplinary measures. The only significant result, in fact, indicates that the Patriots balls were more inflated than the Ideal Gas Law would imply.

By contrast, as shown in table 7, all the results for the Colts are statistically significant at the 5 percent level and are higher than the bottom of the range implied by the Ideal Gas Law for all possible gauge combinations.

The difference between the Patriots pressure drop and the Colts pressure drop, then, is significant, but only because the Colts ball pressure dropped too little rather than because the Patriots ball pressure dropped too much. This can be fully explained by the order in which they were tested. When the Colts balls were sitting in the room, estimated by the Wells report to be between 71

[6] Note that because the starting pressure of the football is a variable in calculating the pressure according to the Ideal Gas Law, it is necessary to make an adjustment to the Ideal Gas Law range stated in the Wells report for cases in which the low gauge was used as the starting gauge. The Ideal Gas Law range is a linear function of the starting pressure: if the starting pressure were 0.4 lower than the 12.5 starting value observed, then the Ideal Gas Law range minimum value should be lower by a factor 12.1 divided by 12.5, since the Wells report calculates the range based on the assumption that the starting pressure was 12.5 and the Ideal Gas Law is a linear function of the starting pressure. However, this adjustment has no effect on the main results: it effectively turns the values displayed for the low pregame gauge assumption into the values that correspond to the high pregame gauge assumption for a given halftime gauge assumption (i.e., the right and left sides of tables 6 and 7 would display the same results displayed on the left side of tables 6 and 7). The only effect is thus to remove the one result that is positive and significant for the Patriots.

Table 7. The Colts Balls at Halftime

		Pregame gauge	
Halftime gauge		High	Low
	High	.825**	1.18**
	Low	.6375*	1.00*

Notes: This table shows the average distance of the halftime measurements of the Colts balls from the bottom of the range implied by the Ideal Gas Law for each of the four possible permutations of pregame and halftime gauges. * indicates significance at a 5 percent confidence level; ** indicates significance at a 1 percent confidence level.
Source: Authors' calculations based on Theodore Wells Jr., Brad S. Karp, and Lorin L. Reisner, *Investigative Report Concerning Footballs Used during the AFC Championship Game on January 18, 2015* (Paul, Weiss, Rifkind, Wharton & Garrison LLP, May 6, 2015), http://online.wsj.com/public/resources/documents/Deflategate.pdf, A-4.

and 74 degrees Fahrenheit, for much of the duration of the 13-minute halftime, their pressure rose (Wells Jr., Karp, and Reisner 2015, XII). The Patriots balls, by contrast, were tested earlier on.

Note that this situation *is* observationally distinguishable from a situation in which the difference in pressure drops can be explained by the Patriots illegally deflating their balls. In such a scenario, you would expect the Patriots balls to measure statistically significantly below the bottom of the range implied by the Ideal Gas Law. You would also expect the Colts ball pressure to not be statistically significantly different from the bottom of the range implied by the Ideal Gas Law. But the Patriots difference is not significant and the Colts difference is significantly *above* the implication of the Ideal Gas Law. This pattern is wholly inconsistent with the conclusions of the Wells report.[7]

An additional piece of statistical evidence also points to the scenario in which there was a non-negligible period of time between the end of the halftime measurement of the Patriots balls and the start of the halftime measurement of the Colts balls. The coefficient on the count variable for the order in which the balls were tested in our regression (N_k) varies in precisely the way that one would expect to observe if the individual Patriots balls were tested in rapid succession, and the individual Colts balls were tested in rapid succession, while the start of the testing of the Colts balls did not follow immediately after the end of the testing of the Patriots balls.

You would expect the order variable to be significant in the regression only when the team variable is excluded, since variation in pressure drop arising from the order of testing would be arising as a consequence of variation in team. This is what the data reveal: in three of the four possible permutations using the stacked data, the regression term for the order in which the balls were tested becomes significant if you exclude the team dummy variable but is insignificant if you include the team dummy variable.

The referees' apparent switching of gauges between the halftime testing of the Patriots footballs and the halftime testing of the Colts footballs further points to the specific scenario of a non-negligible duration of time elapsing between the end of the testing of the Patriots balls and the start of the testing of the Colts balls (Wells Jr., Karp, and Reisner 2015, 69; 116–17). That is, one inference central to the report's conclusion is that the alternative referees, Blakeman and Prioleau, switched gauges between the measurement of the Patriots and Colts balls.

Specifically, according to the report, during halftime Prioleau most likely used the Logo gauge to test the Patriots balls and the Non-Logo gauge to test the Colts balls, and Blakeman most likely used the Non-Logo gauge to test the Patriots balls and the Logo gauge to test the Colts balls (Wells Jr., Karp, and Reisner 2015, 69; 116–17). This switching of the gauges was deduced from the observation that Prioleau registered consistently higher pressure readings for the Patriots, while Blakeman registered consistently higher readings for the Colts. No one present at the time seems to have noticed any switching of the gauges (Wells

[7] The data are also consistent with the hypothesis that the Colts illegally inflated their footballs. But different durations of premeasurement exposure to the temperature of the locker room provide a more parsimonious explanation.

Jr., Karp, and Reisner 2015, 69).[8] Absent a non-negligible duration of time between the end of the testing of Patriots balls and the beginning of testing of the Colts, this unbeknownst switching of the gauges would appear anomalous, if not puzzling.

After all, it becomes easy to imagine how Blakeman and Prioleau switched gauges if a non-negligible length of time passed between the testing of the Patriots and the testing of the Colts balls. On the other hand, if they had started measuring the Colts footballs immediately after they completed measuring the Patriots footballs, it would be more difficult to imagine how or why they would have switched gauges, let alone done so without anyone at the time apparently noticing the gauge switch.

A crucial piece of evidence supporting this scenario was overlooked in the report's analysis. The Colts intercepted a Patriots ball during the first half, and Colts staff thought it felt underinflated. Its pressure was then tested separately from the other 11 Patriots balls. This separate round of testing offers a data point in a setting other than the setting in which the remaining 11 balls were tested. Assuming that the intercepted Patriots ball that was tested was inflated to 12.5 PSI before the game, the average of three measurements derived by this separate measurement process (11.52 PSI) was at the top of the range implied by the Ideal Gas Law, according to the Wells report.[9]

We can quantify how likely it would be for this to occur if we take the conclusions of the Wells report as our null hypothesis. Although the Wells report does not explicitly specify a quantity that the Patriots attempted to deflate the footballs by, the language of the report leaves one with the impression that its authors had in mind a range of 0.45 PSI to 1.02 PSI (Wells Jr., Karp, and Reisner 2015, 114; 9–10).[10] Thus, one could regard deflation of 0.45 PSI as the low-end estimate and about 1.0 PSI as the high-end estimate of the extent to which human-induced deflation occurred.

Suppose one accepts the Wells report assumption that the Non-Logo gauge was used to generate the 12.5 PSI reading before the game. If one also accepts the low end of the range implied in the Wells report—that the Patriots balls had been deflated by about 0.45 PSI—then the intercepted ball should have measured between 11.32 PSI – 0.45 PSI (i.e., 10.87 PSI) and 11.52 PSI – 0.45 PSI (i.e., 11.07 PSI). That is, the intercepted ball should have measured between 10.87 PSI and 11.07 PSI in the low-end case.

If one accepts the high end of the range implied in the Wells report—that the Patriots balls had been deflated by about 1.0 PSI—then the intercepted ball should have measured between 11.32 PSI – 1 PSI (i.e., 10.32 PSI) and 11.52 PSI – 1 PSI (i.e., 10.52 PSI). That is, the intercepted ball should have measured between 10.32 PSI and 10.52 PSI in the high-end case. The standard deviation of the Patriots balls reported at halftime was about 0.4. This means that the average of the measurements, 11.52, is approximately 1 standard deviation above the pressure that the Wells report analysis would predict in the low-end case and approximately 3 standard deviations above the pressure that the Wells report analysis would predict in the high-end case. If one were to assume the facts presented in the Wells report to be correct, then the odds of observing the pressure reported by the Colts are about 1 out of 3 in the low-end case and less than 1 in 300 in the high-end case—that is, quite unlikely.

Summary of Findings

The evidence we present points to a simple—and innocent—explanation for the change in pressure

[8] The Wells report makes clear that this switch became apparent only ex post facto, rather than contemporaneously to the individuals being present. According to the Wells report: "For the reasons stated in Section VII.B and described in detail in Appendix 1, based on Exponent's conclusion that the Logo Gauge generally reports a measurement that is approximately 0.3-0.45 PSI higher than the measurement reported by the Non-Logo Gauge and never produced a reading lower than the Non-Logo Gauge during Exponent's testing, it appears most likely that the two officials switched gauges in between measuring each team's footballs, meaning that Blakeman most likely used the Logo Gauge and Prioleau most likely used the Non-Logo Gauge to test the Colts balls at halftime."

[9] If the Patriots deflated all of their balls measured at halftime except for this one, the odds that the Colts would intercept the clean ball would of course only be 1 in 12, or 8.3 percent. There is no evidence for this having occurred.

[10] According to the report, "When compared to the reported pre-game pressures of 12.5 PSI and 13.0 PSI, respectively, the average pressure drop of the Patriots game balls exceeded the average pressure drop of the Colts balls by 0.45 to 1.02 PSI, depending on various assumptions regarding the gauges used."

in the Patriots footballs. The Patriots balls were measured at the start of halftime, whereas the Colts balls were measured at the end of halftime, after sufficient time had passed for the balls to warm up and return to their pregame pressure. There is no need to consider the alternative hypothesis—that the Colts illegally inflated their footballs—because a simple physical explanation is available.

The fact that the average pressure of the Colts balls was significantly above the prediction of the Ideal Gas Law, while that of the Patriots balls was not, is inconsistent with the findings of the Wells report. Our conclusion that the warming of the balls during halftime is the key factor overlooked in the Wells report is supported by the observation that the readings of the intercepted Patriots football, measured separately from the other Patriots balls, came in almost precisely at the prediction of the law. Under the hypothesis asserted by the Well report, the odds of this Patriots ball matching the Ideal Gas Law prediction were between 1 out of 3 and 1 out of 300. It is therefore unlikely that the Patriots deflated the footballs.

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Appendix I

Assumptions regarding which gauge was used before the game can have consequences for the outcomes of subsequent analysis. For this reason, when preparing data for our linear regression analysis, we made additive or subtractive adjustments of a factor of approximately 0.4 PSI from the raw "unadjusted" values when calculating the difference between the pregame and halftime measurements.

Specifically, for ball k measured by gauge i, and with values for $_{Halftime}PSI_{(k,\,i)}$ extracted from the halftime values reported in table 2 ("Pressure measurements of the footballs as recorded on Game Day") in the Exponent section of the Wells report, we started with the basic formula of calculating the drop between the pregame measurement period and halftime (Wells Jr., Karp, and Reisner 2015, 6):

$$PSI\_drop_{k,i} = {}_{Pregame}PSI_{(k,\,i)} - {}_{Halftime}PSI_{(k,\,i)}$$

In cases in which, for the purposes of analyzing all possible gauge permutations, we assumed that ball k was measured by the high (Logo) gauge before the game but measured by the low (Non-Logo) gauge during halftime, we modified the formula to be:

$$PSI\_drop_{k,i} = {}_{Pregame}PSI_{(k,\,high)} - .4. - {}_{Halftime}PSI_{(k,\,low)}$$

The intuition behind this adjustment is straightforward: the Wells report indicates that the low gauge generates measurements that are approximately 0.4 PSI lower than those of the high gauge (Wells Jr., Karp, and Reisner 2015, 67). To benchmark the measurement obtained from the low gauge at halftime against the measurement obtained before the game with the high gauge, therefore, one must adjust for the measurement discrepancy between the two gauges.

Given that the evidence in the Wells report suggests that a scenario in which the low gauge rather than the high gauge was used to generate the pregame measurement would be one in which the pregame measurement was approximately 0.4 PSI lower than a scenario in which the high gauge was used to generate the pregame measurement, a subtraction of 0.4 PSI from the $_{Pregame}PSI_{(k,\,high)}$ term seems to be the appropriate adjustment in cases in which the halftime measurement is $_{Halftime}PSI_{(k,\,low)}$.

We made the converse adjustment in cases in which, for the purposes of analyzing all possible gauge permutations, we assumed that ball k was measured by the low gauge before the game, but observed the measurement of the high gauge during halftime. In such cases, we modified the formula to be:

$$PSI\_drop_{k,i} = {}_{Pregame}PSI_{(k,\,low)} + .4. - {}_{Halftime}PSI_{(k,\,high)}$$

The intuition behind this adjustment is, again, straightforward: the Wells report indicates that the high gauge generates measurements that are approximately 0.4 PSI higher than those generated by the low gauge. To benchmark the measurement obtained from the high gauge at halftime against the measurement obtained before the game with the low gauge, therefore, one must adjust for this measurement discrepancy between the two gauges.

Given that the evidence in the Wells report suggests that a scenario in which the high gauge rather than the low gauge was used to generate the pregame measurement would be one in which the pregame measurement was approximately 0.4 PSI higher than a scenario in which the low gauge was used to generate the pregame measurement, an addition of 0.4 PSI from the $_{Pregame}PSI_{(k,\,low)}$ term seems to be the appropriate adjustment in which the halftime measurement is $_{Halftime}PSI_{(k,\,high)}$.

Tables A1–A4 present the data used in the linear regressions. The unadjusted PSI drop values are a simple difference of the starting PSI assumption and the observed halftime PSI; the adjusted values take into account the 0.4 difference, per the methodology just described.

Table A1. Assuming Both Teams Start with the High Gauge

Team	Order	Ball	Pregame Gauge	Halftime Gauge	Starting PSI	Halftime PSI	PSI Drop (Unadjusted)	PSI Drop (Adjusted)
Patriots	1	P1	High	Low	12.5	11.5	1	0.6
Patriots	2	P2	High	Low	12.5	10.85	1.65	1.25
Patriots	3	P3	High	Low	12.5	11.15	1.35	0.95
Patriots	4	P4	High	Low	12.5	10.7	1.8	1.4
Patriots	5	P5	High	Low	12.5	11.1	1.4	1
Patriots	6	P6	High	Low	12.5	11.6	0.9	0.5
Patriots	7	P7	High	Low	12.5	11.85	0.65	0.25
Patriots	8	P8	High	Low	12.5	11.1	1.4	1
Patriots	9	P9	High	Low	12.5	10.95	1.55	1.15
Patriots	10	P10	High	Low	12.5	10.5	2	1.6
Patriots	11	P11	High	Low	12.5	10.9	1.6	1.2
Patriots	1	P1	High	High	12.5	11.8	0.7	0.7
Patriots	2	P2	High	High	12.5	11.2	1.3	1.3
Patriots	3	P3	High	High	12.5	11.5	1	1
Patriots	4	P4	High	High	12.5	11	1.5	1.5
Patriots	5	P5	High	High	12.5	11.45	1.05	1.05
Patriots	6	P6	High	High	12.5	11.95	0.55	0.55
Patriots	7	P7	High	High	12.5	12.3	0.2	0.2
Patriots	8	P8	High	High	12.5	11.55	0.95	0.95
Patriots	9	P9	High	High	12.5	11.35	1.15	1.15
Patriots	10	P10	High	High	12.5	10.9	1.6	1.6
Patriots	11	P11	High	High	12.5	11.35	1.15	1.15
Colts	12	C1	High	High	13.1	12.7	0.4	0.4
Colts	13	C2	High	High	13.1	12.75	0.35	0.35
Colts	14	C3	High	High	13.1	12.5	0.6	0.6
Colts	15	C4	High	High	13.1	12.55	0.55	0.55
Colts	12	C1	High	Low	13.1	12.35	0.75	0.35
Colts	13	C2	High	Low	13.1	12.3	0.8	0.4
Colts	14	C3	High	Low	13.1	12.95	0.15	-0.25
Colts	15	C4	High	Low	13.1	12.15	0.95	0.55

Table A2. Assuming Only the Patriots Start with the High Gauge

Team	Order	Ball	Pregame Gauge	Halftime Gauge	Starting PSI	Halftime PSI	PSI Drop (Unadjusted)	PSI Drop (Adjusted)
Patriots	1	P1	High	Low	12.5	11.5	1	0.6
Patriots	2	P2	High	Low	12.5	10.85	1.65	1.25
Patriots	3	P3	High	Low	12.5	11.15	1.35	0.95
Patriots	4	P4	High	Low	12.5	10.7	1.8	1.4
Patriots	5	P5	High	Low	12.5	11.1	1.4	1
Patriots	6	P6	High	Low	12.5	11.6	0.9	0.5
Patriots	7	P7	High	Low	12.5	11.85	0.65	0.25
Patriots	8	P8	High	Low	12.5	11.1	1.4	1
Patriots	9	P9	High	Low	12.5	10.95	1.55	1.15
Patriots	10	P10	High	Low	12.5	10.5	2	1.6
Patriots	11	P11	High	Low	12.5	10.9	1.6	1.2
Patriots	1	P1	High	High	12.5	11.8	0.7	0.7
Patriots	2	P2	High	High	12.5	11.2	1.3	1.3
Patriots	3	P3	High	High	12.5	11.5	1	1
Patriots	4	P4	High	High	12.5	11	1.5	1.5
Patriots	5	P5	High	High	12.5	11.45	1.05	1.05
Patriots	6	P6	High	High	12.5	11.95	0.55	0.55
Patriots	7	P7	High	High	12.5	12.3	0.2	0.2
Patriots	8	P8	High	High	12.5	11.55	0.95	0.95
Patriots	9	P9	High	High	12.5	11.35	1.15	1.15
Patriots	10	P10	High	High	12.5	10.9	1.6	1.6
Patriots	11	P11	High	High	12.5	11.35	1.15	1.15
Colts	12	C1	Low	High	13.1	12.7	0.4	0.8
Colts	13	C2	Low	High	13.1	12.75	0.35	0.75
Colts	14	C3	Low	High	13.1	12.5	0.6	1
Colts	15	C4	Low	High	13.1	12.55	0.55	0.95
Colts	12	C1	Low	Low	13.1	12.35	0.75	0.75
Colts	13	C2	Low	Low	13.1	12.3	0.8	0.8
Colts	14	C3	Low	Low	13.1	12.95	0.15	0.15
Colts	15	C4	Low	Low	13.1	12.15	0.95	0.95

Table A3. Assuming Only the Colts Start with the High Gauge

Team	Order	Ball	Pregame Gauge	Halftime Gauge	Starting PSI	Halftime PSI	PSI Drop (Unadjusted)	PSI Drop (Adjusted)
Patriots	1	P1	Low	Low	12.5	11.5	1	1
Patriots	2	P2	Low	Low	12.5	10.85	1.65	1.65
Patriots	3	P3	Low	Low	12.5	11.15	1.35	1.35
Patriots	4	P4	Low	Low	12.5	10.7	1.8	1.8
Patriots	5	P5	Low	Low	12.5	11.1	1.4	1.4
Patriots	6	P6	Low	Low	12.5	11.6	0.9	0.9
Patriots	7	P7	Low	Low	12.5	11.85	0.65	0.65
Patriots	8	P8	Low	Low	12.5	11.1	1.4	1.4
Patriots	9	P9	Low	Low	12.5	10.95	1.55	1.55
Patriots	10	P10	Low	Low	12.5	10.5	2	2
Patriots	11	P11	Low	Low	12.5	10.9	1.6	1.6
Patriots	1	P1	Low	High	12.5	11.8	0.7	1.1
Patriots	2	P2	Low	High	12.5	11.2	1.3	1.7
Patriots	3	P3	Low	High	12.5	11.5	1	1.4
Patriots	4	P4	Low	High	12.5	11	1.5	1.9
Patriots	5	P5	Low	High	12.5	11.45	1.05	1.45
Patriots	6	P6	Low	High	12.5	11.95	0.55	0.95
Patriots	7	P7	Low	High	12.5	12.3	0.2	0.6
Patriots	8	P8	Low	High	12.5	11.55	0.95	1.35
Patriots	9	P9	Low	High	12.5	11.35	1.15	1.55
Patriots	10	P10	Low	High	12.5	10.9	1.6	2
Patriots	11	P11	Low	High	12.5	11.35	1.15	1.55
Colts	12	C1	High	High	13.1	12.7	0.4	0.4
Colts	13	C2	High	High	13.1	12.75	0.35	0.35
Colts	14	C3	High	High	13.1	12.5	0.6	0.6
Colts	15	C4	High	High	13.1	12.55	0.55	0.55
Colts	12	C1	High	Low	13.1	12.35	0.75	0.35
Colts	13	C2	High	Low	13.1	12.3	0.8	0.4
Colts	14	C3	High	Low	13.1	12.95	0.15	-0.25
Colts	15	C4	High	Low	13.1	12.15	0.95	0.55

Table A4: Assuming Both Teams Start with the Low Gauge

Team	Order	Ball	Pregame Gauge	Halftime Gauge	Starting PSI	Halftime PSI	PSI Drop Unadjusted	PSI Drop Adjusted
Patriots	1	P1	Low	Low	12.5	11.5	1	1
Patriots	2	P2	Low	Low	12.5	10.85	1.65	1.65
Patriots	3	P3	Low	Low	12.5	11.15	1.35	1.35
Patriots	4	P4	Low	Low	12.5	10.7	1.8	1.8
Patriots	5	P5	Low	Low	12.5	11.1	1.4	1.4
Patriots	6	P6	Low	Low	12.5	11.6	0.9	0.9
Patriots	7	P7	Low	Low	12.5	11.85	0.65	0.65
Patriots	8	P8	Low	Low	12.5	11.1	1.4	1.4
Patriots	9	P9	Low	Low	12.5	10.95	1.55	1.55
Patriots	10	P10	Low	Low	12.5	10.5	2	2
Patriots	11	P11	Low	Low	12.5	10.9	1.6	1.6
Patriots	1	P1	Low	High	12.5	11.8	0.7	1.1
Patriots	2	P2	Low	High	12.5	11.2	1.3	1.7
Patriots	3	P3	Low	High	12.5	11.5	1	1.4
Patriots	4	P4	Low	High	12.5	11	1.5	1.9
Patriots	5	P5	Low	High	12.5	11.45	1.05	1.45
Patriots	6	P6	Low	High	12.5	11.95	0.55	0.95
Patriots	7	P7	Low	High	12.5	12.3	0.2	0.6
Patriots	8	P8	Low	High	12.5	11.55	0.95	1.35
Patriots	9	P9	Low	High	12.5	11.35	1.15	1.55
Patriots	10	P10	Low	High	12.5	10.9	1.6	2
Patriots	11	P11	Low	High	12.5	11.35	1.15	1.55
Colts	12	C1	Low	High	13.1	12.7	0.4	0.8
Colts	13	C2	Low	High	13.1	12.75	0.35	0.75
Colts	14	C3	Low	High	13.1	12.5	0.6	1
Colts	15	C4	Low	High	13.1	12.55	0.55	0.95
Colts	12	C1	Low	Low	13.1	12.35	0.75	0.75
Colts	13	C2	Low	Low	13.1	12.3	0.8	0.8
Colts	14	C3	Low	Low	13.1	12.95	0.15	0.15
Colts	15	C4	Low	Low	13.1	12.15	0.95	0.95